The FY2000 Office of Naval Research SECNAV/CNO Chair and ONR/MIT Scholar of Oceanographic Sciences

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LONG-TERM GOALS

Our long-term goals are to:

(1) to develop physics based algorithms which improve the performance of US Navy sonar systems.

(2) to promote the coupling between the basic and applied (6.1 and 6.2) and to operational systems used for USN sonar systems.

OBJECTIVES

The technical objective of the proposal is to optimize the performance of both sonar and ocean remote sensing systems by coupling physical and statistical environmental models to state of the art, physics based, signal and array processing methods. This objective has long been sought; however, it has been quite difficult to attain. At one extreme, acoustical oceanographers conduct detailed geoacoustic observations and process studies with little concern upon their impact, while at the other extreme, sonar signal processors typically use the simplest environmental models which ignore much of what is known about the acoustic medium in which the signal and noise fields propagate.

APPROACH

Our primary approach has been to conduct basic research in ocean acoustics that combines statistical signal processing, wave propagation and scattering. To assist us in this purpose and to support the next generation of researchers in acoustical oceanography, we have opened and filled a position for a new Postdoctoral Fellow. The Fellow was chosen after a national search was advertised under the auspices of the SECNAV/CNO Chair/Scholar Award. Five candidates were interviewed from a pool of twenty qualified applicants. Dr. Aaron Thode from the Marine Physical Laboratory of Scripps Institution of Oceanography was selected to fill the position. He has worked for the past year under the direct supervision of the SECNAV/CNO Scholar. His accomplishments over the past year are presented later in this document. Last spring we conducted a search for another Postdoctoral Fellow under the SECNAV/CNO Chair/Scholar Award, but found no appropriate candidates.

WORK COMPLETED AND RESULTS

The following is a list of Navy interactions enabled by SECNAV/CNO Chair:

1) Acoustical Observatory: The SECNAV/CNO Chair has led a panel of national experts on oceanography, acoustics and sonar signal processing for the development of an "acoustic observatory." The overall objective of the observatory is to understand all issues required for the USN to maintain acoustic superiority with its systems. This panel was the direct result of a JASON summer study in 1997 and the Naval Studies Board Report, "Technology..... for Navy 21." Phase I was completed in December 1998. Funding was established for Phase IIA in October 1999. Many of the fundamental issues that limit performance of sonar arrays were identified. The results were briefed at the Acoustic Superiority Meeting on April 2000. Two programs, one at DARPA ATO and one at ONR Code 321 Undersea Signal Processing are now being established as the result of this panel.

2) The SECNAV/CNO Chair became a member of both the Ocean Studies Board (OSB) and the Naval Studies Board (NSB) for the National Research Council.

3) Submarine Superiority Technical Advisory Group: The SECNAV/CNO Chair is a member of this panel for N87. It provided advise to N87 on the APB (Advanced Processor Build) / ARCI Acoustic Rapid COTS Insertion) for submarine sonars. The SECNAV/CNO Chair was a member of the original CNO Sonar Panel, which recommended the APB/ARCI process to improve the performance of submarine sonars.

4) NRC Undersea Weapons: The SECNAV/CNO Chair is a member of the Naval Studies Board panel reviewing Undersea Weapons. The findings of the panel will soon be submitted for National Academy review.

5) Sonar Systems and Oceanography Training: The SECNAV/CNO Chair is working with SUBLANT and SUBDEVRON-12 to develop a short course for COs and XOs on how the oceanographic environment influences the performance of the sonar systems, especially the APB/ARCI systems. The Chair met with both NAVOCEANO and SUBDEVRON in preparing for this.

6) Special panels: The SECNAV/CNO Chair interacts with several USN panels whose objectives are classified.

Activities of the Scholar:

Professor Makris has used SECNAV funds to help initiate new collaboration with US Allies in Australia and Asia as well as Europe through NATO. The purpose of these collaborations is to bolster ONR Programs in Passive and Active Detection and Localization including the study of Acoustic Reverberation in Shallow Water. He has also strengthened ties between leading universities, such as MIT and Penn State, with leading government research laboratories, such as NUWC RI and NRL DC, in ocean acoustics by having them jointly participate in the ONR Geoclutter Program, for which he is the Chief Scientist in Acoustics. Ties have also been strengthened between ONR Geophysicists and ONR Underwater Acousticians through this program.

(1) Professor Makris has used the SECNAV/CNO Scholar position to bolster collaboration with the world renowned Australian underwater ambient noise expert Dr. Douglas Cato, of the Defence Science and Technology branch of the Australian government. The collaboration includes joint work on ambient noise generation and measurement in hurricane conditions, for which little data and theory exists as well as joint work on marine mammal ambient noise issues.

(2) Professor Makris traveled to Singapore on invitation of their government to help them assess a major initiative they are sponsoring on "Acoustic Daylight" detection of underwater intruders. Professor Makris found the technology to be extremely limited and fundamentally flawed. Professor Makris used the opportunity to establish a joint research program with the Defence Science Organization of the Singapore Government by allowing them to participate in the upcoming ONR Geoclutter Program at Singapore's expense.

(3) Professor Makris helped coordinate the ONR ASIAEX program during a stop in Taiwan by insuring that Taiwanese underwater acousticians could participate in oceanographic field experiments of the program.

(4) Professor Makris has strengthened ties with the NATO SACLANT Undersea Research Centre by securing SACLANT's participation in the ONR Geoclutter Program through use of the RV Alliance in the ONR STRATAFORM area in a major shallow water reverberation experiment to be conducted in April-May 2001. The program will include the use of MACE sources and towed horizontal receiving arrays.

(5) Professor Makris has also helped coordinate a reverberation experiment using a US Navy Destroyer in the STRATAFORM area to be conducted jointly with NUWC in the first quarter of 2001.

Prof. Makris is currently supervising the Post Doctoral Fellow, Dr. Aaron Thode, as well as four new graduate students under SEC/NAV funds. These new personnel are currently working on problems in ocean-acoustic remote sensing.

The following is a summary of research conducted by the Scholar this year, which has lead to a number of submitted papers:

(A) Statistical Ocean Acoustics

This work continues from last year. In particular, necessary conditions for localization and classification estimators to become asymptotically unbiased and attain minimum variance, i.e. the Cramer-Rao lower bound (CRLB), have been developed from statistical estimation theory using higher order asymptotic inference. The conditions have been applied to solve a fundamental problem in signal processing, i.e. conditions necessary for the matched filter, used extensively in radar and sonar target range estimation, to attain the CRLB. It was found that the matched filter attains the CRLB when the SNR exceeds the kurtosis of the signal's energy spectrum. The Doppler shift estimator was also shown to have dual behavior. They have also been used to determine conditions necessary for ocean-acoustic matched field range and depth localization estimates to become unbiased and attain the CRLB. It was found that most matched field range-depth estimates in shallow water typically have severe biases that are not accounted for in current signal processing algorithms and that they do not attain minimum variance, i.e. the CRLB, unless the SNR is extremely high. In particular, Prof. Makris and his Post-Doctoral fellow and students have shown that when matched field processing is used to estimate the range and depth of a source in an ocean waveguide, significant biases in depth estimation can occur and that the Cramer-Rao bound provides an unrealistically optimistic estimate of the true range and depth variances unless the signal to noise ratio is very high. These findings have been in reported in papers recently submitted to the Journal of the Acoustical Society of America. Some of the more purely statistical and theoretical aspects of the work are still in progress, but will be submitted to the Journal of the Royal Statistical Society B shortly.

(B) A Unified Model for Reverberation and Submerged Target Scattering in a Stratified Ocean Waveguide

This work also continues from last year. Professor Makris and his students have shown that the sonar equation, probably the most widely used predictive tool in active acoustics, typically cannot be used in shallow waveguides and can lead to overestimates in target returns by many orders of magnitude. This is because it assumes that propagation and scattering effects can be factored from each other. This is not typically possible in shallow water environments where multipath or modal propagation is involved. To address this problem, a unified model for reverberation and submerged target scattering in a stratified medium has been developed rigorously from Green's theorem. This is the first model that can treat returns from a deterministic or fluctuating target as well as stochastic returns from a randomly rough seafloor in a unified manner. Previous formulations reported inconsistencies in level between deterministic returns from a submerged target and expected returns from a random seafloor. Simulation results indicate that the detection of submerged target echoes above diffuse seafloor reverberation is highly dependent upon water column and sediment stratification as well as array aperture, source, receiver and target locations in addition to the scattering properties of the target and seafloor. Rigorous expressions for the broadband field scattered from a deterministic or fluctuating target in a stratified ocean waveguide have been derived from Green's theorem using the saddle point asymptotic method. The expressions enable the unified model to be generalized to broadband analysis for both target returns, boundary and volume reverberation. The expressions facilitate broadband analysis since they circumvent the need to perform Fourier transforms. These results have been submitted for publication in the Journal of the Acoustical Society of America.

Portions of this research have also been conducted to support a proposal for the ONR Geoclutter Program and the ONR Underwater Signal Processing Program.

(C) Spectral and Modal formulations for the Doppler-Shifted Field Scattered by an Object Moving in a Stratified Medium

A rigorous formulation for the Doppler shifted field scattered from a moving target insonified by a moving source and received by a moving sensor in a stratified ocean waveguide has been developed from Green's theorem. This formulation will enable estimates of target velocity to be made in a shallow water waveguide. The advantage of an active system over a passive system in target velocity estimation is that the frequency of the source is known in the active system but not in the passive system. Target detection by Doppler shift estimation may also prove to be advantageous in discriminating targets from seafloor clutter. This task, however, is too involved to be investigated in the current project. Both spectral or wavenumber and modal formulations have been derived directly from Green's theorem. Results indicate that for a shallow water waveguide consisting of n propagating modes, there will be roughly n^2 Doppler shifted frequencies from a moving target. The Doppler shifted frequencies will depend on the velocity of the source, receiver and target. The nature of the Doppler shifted field scattered from the target will be highly dependent on the shape of the target as well as its motion and the number of trapped modes in the waveguide.

(D) Forward Scatter Theorem in A Stratified Medium

A rigorous formulation of the forward scatter theorem, also known as the extinction theorem or optical theorem in free space applications, has been developed for an object in a waveguide using Green's theorem. The theorem is essential to enable accurate modeling of the detection of targets using the forward-scattered field in shallow water. The results indicate that estimates of the scattering cross-section of a target in a waveguide using the forward-scattered field will typically lead to significantly different results from those obtained for the same target in free space or deep water. This result will impact all target detection processing algorithms used in shallow water that are based on exploitation of the forward-scattered field.

(E) Detection and Classification of Hurricanes by Passive Underwater Acoustics

Professor Makris has developed a program to determine whether hurricanes and tropical cyclones can be detected and classified by use of passive acoustic techniques developed during the cold war. Professor Makris and his students have derived analytic expressions for the ambient noise field and its moments generated by a tropical cyclone. They have used these expressions to perform simulations to determine whether tropical cyclones can be detected and classified using underwater hydrophone arrays in regions such as the Indian Ocean where satellite surveillance is too sparse to adequately track these storms. The acoustic techniques may also provide better means of estimating the destructive potential of tropical cyclones than current image processing techniques that make estimates based on the size of the storm's eye from satellite imagery. This work is being done in collaboration with one of the world's leading hurricane experts Prof. Kerry Emmanuel of MIT's Earth and Planetary Science Department. Current plans are to also make measurements of ambient noise level versus wind speed since these measurements do not exist for wind speeds exceeding 30 knots, while hurricanes typically have maximum wind speeds exceeding 100 knots. The measurements will be made in the laboratory, in a new tank developed to study air-sea interaction in hurricane wind states, and in planned field experiments in actual hurricanes.

Work completed by Post Doctoral Fellow:

A) Bias and variance of estimates extracted from acoustic data.

In conjunction with work by Professor Makris, computed the theoretical bias and variance of parameters estimated from inversions from acoustic data collected from a vertical array in an acoustic waveguide. These inversions include source range, depth, bottom geo-acoustic properties, and sound-speed profile inversion. Demonstrated that as the energy ratio of received signal to additive noise (SANR) descends to the lower operational range of a passive array, source range and depth estimates exhibit significant biases and have variances that exceed the Cramer-Rao bound by orders of magnitude. Also demonstrated that an optimum source range exists for estimation of ocean bottom parameters.

B) Developed a new passive acoustic localization technique that requires no propagation modeling.

Derived, demonstrated, and published a method for passively ranging an acoustic source in a waveguide, without detailed knowledge of the propagation environment, as is currently required by matched-field processing methods. Currently applying for a U.S. Patent on the concept.

C) Tracking of sperm whales using a towed array in the Gulf of Mexico.

In June-July 2000 supervised the use of an acoustic array for surveying and tracking sperm whale pods in the Gulf of Mexico. Wrote software to allow frequency-domain beamforming for Ishmael, a general localization software package developed by David Mellinger for the Windows environment. Demonstrated a capability to follow a group of animals for three days and two nights, recorded social sounds concurrently with sounds recorded by an acoustic tag on one of the animals, and recorded and labeled various types of anthropogenic sounds the animals were exposed to over the tracking period. Currently attempting to extract dive profiles from data collected on the array, using triangulation from surface and bottom reflections. Follow-up cruise expected in 2001.

D) Collection of DIFAR sensors for localization studies of right whales

Obtained DIFAR sonobuoys and salvaged sensors for use in right whale behavioral studies in the Bay of Fundy. Currently working on software to allow use of sensors in the field to localize sperm and right whales.

Invited talks of the Chair:

1) March 2000, “The state of the art in matched field processing,” IEEE Conference in Adaptive Array Processing

2) March 2000, “Acoustics and ONR,” Heinz Lecture Series at Woods Hole, Oceanography the Making of a Science.

3) April 2000, “Acoustic Testbed,” Acoustic Superiority Workshop.

4) June 2000, “Matched field processing with Doppler and the degrees of freedom in an acoustic channel,” Spring 2000 Meeting of the Acoustical Society of America (ASA).

5) October 2000, “Stochastic Matched Field Processing for Detection and Nulling in Uncertain Ocean Environments,” Asilomar 2000 Conference.

Invited talks of the Scholar:

(1) January 2000, "A unified model for reverberation and submerged object scattering," Defence Science and Technology Organization, Sydney Australia

(2) January 2000, "Geological Clutter," Defence Science Organization, Singapore.

(3) January 2000, "Where the Acoustic daylight Analogy Breaks Down," Taiwan National University, Taipei Taiwan.

(4) August 2000, “Scattering, Reverberation and Extinction in an Ocean Waveguide, Including both Moving and Stationary Targets,” Applied Physics Laboratory, University of Washington, Washington.

(5) August 1999, " A unified model for reverberation and submerged object scattering from both deterministic and fluctuating targets," ONR Signal Processing Peer Review, CLASSIFIED, University of Washington, Washington.

(6) September 2000, "The ONR Geoclutter Program," SACLANT Undersea Research Center, La Spezia, Italy.

Contributed talks of the Chair

1) D. Kilfoyle, J. Preisig and A. B. Baggeroer, “Spatial modulation using vertical arrays in an underwater telemetry channel,” 2000 Spring Meeting of the Acoustical Society of America.

2) W. Xu and A. B. Baggeroer, “Weiss-Weinstein bound for matched-field parameter estimation,” 2000 Spring Meeting of the Acoustical Society of America.

Contributed talks of the Scholar

(1) E. Naftali and N. C. Makris, “First order bias and second order variance of maximum likelihood time delay and Doppler shift estimates,” 2000 Spring Meeting of the Acoustical Society of America.

(2) P. Ratilal and N. C, Makris, “A unified model for reverberation and submerged target scattering in shallow water,” 2000 Spring Meeting of the Acoustical Society of America. **Won Best Student Paper Award.**

(3) Y. Lai and N. C. Makris, “Multiple Doppler shifts in the field scattered from an object moving in a horizontally stratified waveguide,” 2000 Spring Meeting of the Acoustical Society of America.

(4) A. Thode, E. Naftali and N. C. Makris, "Theoretical first-order bias and second-order variance for localization estimates from matched-field processing methods: Randomized signal," 2000 Spring Meeting of the Acoustical Society of America.

(5) P. Ratilal and N. C. Makris, "A unified model for reverberation and submerged target scattering in a stratified ocean waveguide," European Conference on Underwater Acoustics 2000, Lyon, France.

(6) E. Thode, E. Naftali and N. C. Makris, "Conditions for Ocean Acoustic Matched Field Inversions to be Unbiased and have Minimum Variance," European Conference on Underwater Acoustics 2000, Lyon, France.

(5) N. C. Makris and E. Naftali, "Conditions for ocean acoustic matched field inversions to be unbiased and attain the Cramer-Rao bound," 1999 Fall Meeting of the Acoustical Society of America

(6) P. Ratilal and N. C. Makris, "Validity of the sonar equation and Babinet's principle for object scattering in a shallow water waveguide," 1999 Fall Meeting of the Acoustical Society of America

Contributed talks of Post Doctoral Fellow

"Source ranging with minimal environmental information using the virtual receiver and waveguide invariant concepts," A.M. Thode. Presented at Atlanta, GA, ASA Conference, May 2000.

"Three-dimensional localizations of blue whale calls off the Channel Islands", A.M. Thode, G.L. D'Spain, W.A. Kuperman, Dec. 1999. Presented at 13th Biennial Conference on the Biology of Marine Mammals, Wailea, Maui, Hawaii.

"Short duration FM sounds recorded from blue whales (*Balaenoptera musculus*) in Peruvian waters", Tom Norris, A.M. Thode, Jay Barlow, Dec. 1999. Presented at 13th Biennial Conference on the Biology of Marine Mammals, Wailea, Maui, Hawaii.

"Rapid estimation of dolphin whistle bearings using a sparse towed hydrophone array" , A.M. Thode, T. Norris, J. Barlow. Presented at Columbus, OH, ASA Conference, October 1999.

"Three-dimensional tracking of two blue whales using MFP and a tilted vertical array" , A.M. Thode, T. Norris, J. Barlow. Presented at Columbus, OH, ASA Conference, October 1999.

PUBLICATIONS

(1) C. S. Chia, N. C. Makris, L. T. Fialkowski, "A comparison of bistatic scattering from two geologically distinct abyssal hills," J. Acoust. Soc. Am. (to appear Nov 2000)
(2) N. C. Makris and P. Ratilal, "A unified model for reverberation and submerged target scattering in a stratified ocean waveguide," submitted to J. Acoust. Soc. Am.
(3) E. Naftali and N. C. Makris, "Necessary conditions for a maximum likelihood estimate to become asymptotically unbiased and attain the Cramer-Rao lower bound, Part I: General approach with an application to Time-Delay and Doppler shift estimation," submitted to J. Acoust. Soc. Am.
(4) A. Thode, E. Naftali, I Ingram, P. Ratilal and N. C. Makris, "Necessary conditions for a maximum likelihood estimate to become asymptotically unbiased and attain the Cramer-Rao

lower bound, Part II: Range and depth localization of a sound source in an ocean waveguide," submitted to J. Acoust. Soc. Am.
(5) Y. Lai and N. C. Makris, "Spectral and modal formulation for the Doppler-shifted field scattered by an object moving in a stratified medium," submitted to J. Acoust. Soc. Am.
(6) P. Ratilal and N. C. Makris, "Extinction theorem for object scattering in a stratified medium," submitted to J. Acoust. Soc. Am.
(7) D. Kilfoyle and A. B. Baggeroer, "The state-of-the-art of acoustic telemetry," *IEEE J. Ocean. Eng.* 25, pp 1-24 (Jan 2000).
(8) A.M.Thode, W.A. Kuperman, Gerald L. D'Spain, William S. Hodgkiss, "Localization using Bartlett matched-field processor sidelobes" J. Acous. Soc. Am. 107 (1), 278-286, Jan. 2000.
(9) "Matched-Field processing, source signature recovery, and geoacoustic inversion of blue whale vocalizations"-A.M.Thode, Gerald L. D'Spain, W.A. Kuperman, J. Acous. Soc. America, 107(3), 1286-1300, Mar. 2000.
(10) A.M. Thode, T. Norris, J. Barlow, "Beamforming on dolphin whistles using a sparse hydrophone array", J. Acous. Soc. Am., 107(6),3581-3584, June 2000.
(11) A. Thode, "Source ranging with minimal environmental information using a virtual receiver and waveguide invariant theory". J. Acous. Soc. Am. 108(4), 1582-1594, October 2000